Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24**, 151–175 (1999)

SOIL CREEP: PROBLEMS RAISED BY A 23 YEAR STUDY IN AUSTRALIA

M. F. CLARKE[1], M. A. J. WILLIAMS[2*] AND T. STOKES[3]

[1]*South Lodge, Shobrooke Parke, Crediton, Devon, EX17 1AF, UK*
[2]*Mawson Graduate Centre for Environmental Studies, The University of Adelaide, South Australia 5005, Australia*
[3]*Department of Geography and Environmental Science, Monash University, Clayton, Victoria 3168, Australia*

Received 18 March 1994; Revised 29 May 1998; Accepted 16 July 1998

ABSTRACT

In October 1965 and February 1966, 55 Young-pits were installed in tropical Northern Territory (NT) and temperate New South Wales (NSW). Pits were monitored in 1968, 1971 and 1974; also, for the NT only, in 1988. In each region, half of the pits are on weathered granite, and half on sandstone. Local relief is 30m or less, and slopes are up to 20°. Annual rainfall is evenly distributed in the NSW sites (800mm a^{-1}), but is confined to the five to six month wet season in NT (1200mm a^{-1}). Six pits suffered external disturbance and so were not analysed. Analysis of 160 rods in 49 undisturbed pits shows: (1) vectorial movement generally not downslope parallel to the ground surface, but dominated by a vertically downward component; (2) significant uphill and vertically upward components of movement for many rods; (3) a weak correlation between total movement and sine of slope; (4) rapid movement during 1965–68, and slow movement thereafter; (5) significantly higher creep rates on the NT granites than on all other sites, perhaps because mound-building termites are especially active there. We conclude that our data do not support soil creep models which assume that all movement is downslope and slope-parallel. Repeated long-term measurements are essential to distinguish long-term creep rates from the short-term effects of disturbance. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS soil creep; Young-pit; hillslopes; upslope movement; Australia; granite; sandstone; termites

INTRODUCTION

Soil creep is generally conceived to be a slow, discontinuous, downslope movement of regolith resulting from disturbance of particles under the influence of gravity. Possible causes of disturbance include: (a) expansion and contraction due to wetting and drying, heating and cooling, or freeze–thaw activity; (b) growth and decay of plant roots; (c) faunal activity; (d) loss of volume occasioned by eluviation of particles in suspension or solution. Although factors (b), (c) and (d) may cause movement of soil in any direction, factor (a) is considered to produce net motion downslope, parallel to the ground surface (e.g. Culling, 1965, 1983a, b, c; Kirkby, 1967; Washburn, 1967; Young, 1972) and the resultant motion from all causes is also, explicitly or tacitly, regarded as directed downslope.

Most research into soil creep indicates that the magnitude of creep decreases from a maximum at the ground surface to zero at, or close to, bedrock or some other assumedly cohesive, immobile material (Kirkby, 1967; Jahn, 1989). Hitherto, the form of a creep profile, based on measurements parallel to the surface slope, has been portrayed as convex, concave or convexo-concave (Young, 1960; Kirkby, 1967; Barr and Swanston, 1970; Eyles and Ho, 1970). Exceptions to these normative statements about soil creep have been published. Auzet and Ambroise (1996) used specially designed strain gauge probes during a seven month study of a forested slope in the Vosges mountains of France to demonstrate the strongly discontinuous, seasonal and highly reversible character of creep movements, a conclusion foreshadowed by Finlayson (1981), who observed an upslope component for creep at some of his sites. However, since the duration of his study was only nine months, and that of Auzet and Ambroise only

* Correspondence to: Prof. M. A. J. Williams, Muawson Graduate Centre for Environmental Studies, University of Adelaide, South Australia 5005, Australia.

CCC 0197-9337/99/020151–25 $17.50

seven months, it is possible that such upslope movements may not be representative of movements over a period of several years. Our 23 year study overcomes this inherent disadvantage of short-term observations. Young (1978) found that creep in a pit resurveyed after 12 years was not parallel to the surface slope but 14° from vertically downward. Culling (1983b) contrasts the engineer's conception of creep (directed, strong and persistent) with that of the geomorphologist (random, intermittent and weak). Finlayson (1985) provides a useful summary of research up to 1983. More recent studies by Moeyersons (1988, 1989) in Rwanda and by Verster and Van Rooyen (1988) in South Africa indicate a vertically downward as well as an upslope component to the movement of many of the buried rods considered to reflect the net movement of the creeping soil mantle. In addition, Moeyersons (1988) observed pockets of highly irregular subsoil creep movements that he believed had more in common with some form of turbulent flow than with the type of laminar flow often invoked for a mantle of soil creeping downhill parallel to the ground surface.

This study arose from an initial comparative study of rates of hillslope erosion on granite and sandstone slopes in tropical northern and temperate southeastern Australia (Williams, 1973). A key conclusion from this three year study (1965–68) was that creep rates did not differ significantly between the localities except for the northern granite slopes, where soil creep was significantly faster than on the southern granite slopes. This study was designed to test the validity of these preliminary results by extending the period of observation from three to nine and in some cases to 23 years.

In October 1965 and February 1966, 55 Young-pits were installed in tropical Northern Territory (NT) and temperate New South Wales (NSW). Pits were monitored in 1968, 1971 and 1974; also, for the NT only, in 1988. The total period of monitoring was 9 years in NSW and 23 years in NT. The aim of this paper is to present and evaluate the results from these long-term experiments within the context of previous field observations of rates of soil creep.

STUDY AREAS

Data for this study were obtained from four localities: two in the seasonally wet tropical Northern Territory (NT) and two on the temperate Southern Tablelands of New South Wales (NSW) (Figure 1). In each case, one set of sites was located on granite and another set on sedimentary rocks dominated by sandstone. The reason for this choice was to test the hypothesis that the influence of bedrock lithology might outweigh that of regional climate in determining overall rates of soil creep (Williams, 1969a, 1973).

The NT localities lie between 150 and 200 km southeast of Darwin. The granite sites are located 100 to 130 m above sea level and on a deeply weathered Cainozoic erosion surface (Williams, 1991). The sandstone sites, approximately 40 km east of the granite sites, are in the eroded foothills zone of a deeply weathered and dissected plateau situated between 100 and 200 m above sea level.

The far north of NT is a region of climatic extremes with five months of heavy tropical rainfall alternating with seven months of almost total drought (Haynes *et al.*, 1991). At Brocks Creek mean annual rainfall (1898 to 1941) was 1235 mm, of which 92 per cent fell during the period November to March. During the period of study mean annual rainfall at Pine Creek, a locality with similar precipitation regime, was approximately 1180 mm, ranging from 650 mm to about 1700 mm in the wet seasons of 1969–70 and 1973–74 respectively. There was no significant variation in total mean values for the three intervals between exhumation of pits, and this region has the least variable rainfall regime anywhere in Australia (Jennings, 1967). Highest temperatures (mean daily maximum 39°C) occur in November just before the rains and remain high during the wet season, after which they fall to a mean daily minimum of 13°C in July. In the wet season relative humidity is high (>80 per cent at 09:00 and >65 per cent at 15:00 hours). The rate of evaporation increases during the dry season, attaining 230 mm per month, and total yearly pan evaporation is about 2000 mm (Haynes *et al.*, 1991).

In the long dry season plant growth slows down or ceases and grass fires rage through the savanna woodland, so that at the onset of the wet season the soils are bare and dry, offering little resistance to erosion by torrential convectional rains (Williams, 1969b). As the wet season progresses plant growth

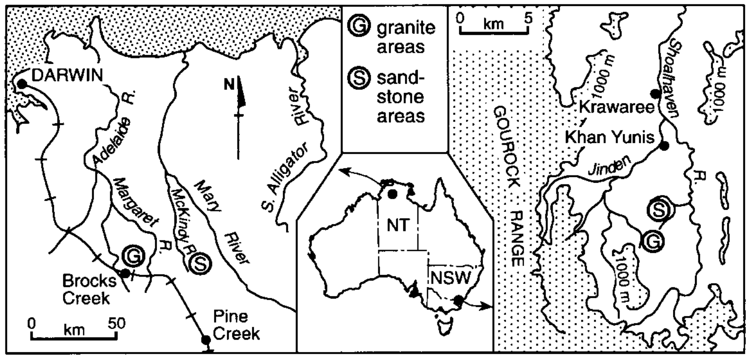

Figure 1. Location of the study areas

takes place rapidly, soil detachment by raindrop impact diminishes and the intermittently near-saturated ground becomes prone to creep and other more rapid forms of mass-movement.

The NT granite locality has convex slopes and shallowly incised drainage. Slopes in the granite area are gentle, ranging from 0·5° to 5°. Mound-building termites are very active during the wet season. The soils, which appear to be biogenic (Williams, 1968, 1978a), are three-layered with a mobile sandy topsoil (M horizon) overlying a stony quartz layer (S horizon), beneath which is a clayey subsoil formed from granite weathered *in situ* (W horizon). Termite activity occurs in all four localities but is only significant in the NT granite area. Williams (1978a) concluded that termites are responsible for the three-layered soils characteristic of the granite landsurface. The lower (W) soil horizon is weathered granite, forming clay loam or sandy clay loam from which mound-building termites remove sand, silt and clay. Eventual collapse of termite mounds provides material which, redistributed and partly leached of clay by slopewash, forms an upper (M) horizon of loamy coarse sand. A stony (S) horizon between the M and W layers consists largely of vein quartz fragments, too coarse for removal by termites, in a matrix of material similar to that of the W horizon but lacking signs of the original granite fabric and structure. (We refer to these soils again when discussing rates of creep on the NT granite hillslopes.)

The NT sandstone sites are situated in a landscape of steep strike-ridges and flat-floored valleys. Local relief is 30m or less and hillslope gradients range from 5° to 20°, the characteristic angle being 10° to 11°. Hillslope soils are formed from weathered sandstone and shales capped by a sandstone boulder-mantle. Texture-contrast soils, in places weakly solodic or solonetzic, are developed on colluvial/alluvial flats. Hard-setting during the dry season, soils become intermittently near-saturated and non-cohesive during the wet season, when they are very susceptible to localized gully erosion.

Eucalyptus miniata and *E. tetrodonta* form an open-canopied woodland up to 12m high over the deeper, better-drained granite soils. On the steeper granite slopes, where topsoil has been eroded and the quartz stone layer exposed, trees are stunted and grass cover is sparse. A mixed woodland community including *E. latifolia, E. terminalis* and *E. foelscheana* dominates the sandstone and shale hillslopes. Trees are taller and more scattered on the alluvial flats which support a relatively dense cover of grasses during the wet season.

The sites in the Southern Tablelands of NSW are located approximately 80km southeast of Canberra on two low hills near the headwaters of the Shoalhaven River at an altitude of 850–1000m. The hills lie on either side of a lithological boundary between granite and Devonian sandstones interbedded with shales. The hills are dissected by broad, flat-floored grassy channels and surrounded by poorly drained, treeless, colluvial–alluvial flats supporting grassland dominated by *Themeda australis* and *Poa caespitosa*. On the granite hill wet sclerophyll forest is dominated by *E. fastigata* and *E. robertsonii*. Beneath the dense canopy is a discontinuous ground cover. An open canopied, dry sclerophyll forest of *E. dalrympleana* and *E. robertsonii* with a relatively sparse ground cover clothes the sandstone hill.

The climate is characterized by cold winters, warm summers and an even rainfall distribution. Mean annual precipitation at Krawaree, about 10km north of the study area, was 804mm (1901–65) with 54 per cent falling in the summer half of the year. However, evaporation in summer is up to four times greater than in winter, so that soils are more frequently wet in winter than in summer. Mean monthly temperatures are estimated to range from 3°C in July to 16°C in January. Local data on the frequency of frosts are not available but a reasonable estimate for the study area is up to 100 frosts per annum, so that there may be several occasions each year when freeze–thaw activity could affect the uppermost portion of soils. Repeated measurements of soil temperature in 1967 showed that such activity is confined to a depth of 2 or 3cm at the most and the frequency of freeze–thaw cycles would be far lower than the frequency of frosts (Washburn, 1973, pp. 58, 60; Embleton and King, 1968, pp. 450–451).

In the granite area soils are developed in colluvium overlying decomposed granite. The colluvium appears to consist of two or more sedimentary layers (Williams, 1978b) of which the topmost is a loam, the lower layers being sandy or silty clay loam, or clay loam. On the poorly drained footslopes gleyed subsoils possess a coarse columnar structure. Soils on the hillslopes of the sandstone area are generally shallower than those on the granite hill, ranging from skeletal lithosols on the steepest slopes, through shallow gravelly or stony loams on moderate slopes, to deeper uniform loams on the colluvial footslopes. In the shallow depressions between spurs a loamy topsoil lies over a subsoil of sandy clay loam.

METHODS

Measurement technique

We used Young-pits to measure soil creep (Young, 1960; Williams, 1973). A vertical row of 460mm long steel rods, 4·8mm in diameter, was hammered horizontally and parallel to the surface contour into a pit wall so that the exposed ends of the rods lay in the plane of steepest slope. In each pit the lowest horizontal rod and a vertical rod through the base of the pit were forced into bedrock or apparently undisturbed regolith-rotted rock whose fabric showed structural continuity with underlying bedrock. Some soil water may drain laterally from the undisturbed soil in which the rods were inserted into the back-filled pit of reworked soil, but it seems very unlikely that there would be significant sideways flow at right angles to the line of steepest hydraulic gradient. It was almost always very hard to detect much sign of disturbance in the back-filled soil materials when exhuming the pits. There were no obvious differences in terms of moisture, colour, consistence and structure after the lapse of three years, so that great care was needed during exhumation.

The pits were initiated in October 1965 in the north (NT), with 16 pits (72 rods) on granite and 13 pits (52 rods) on sandstone; and in February 1966 in the south (NSW), with 14 pits (56 rods) on granite and 15 pits (63 rods) on sandstone. The pits were reopened in February 1968 (NSW) and May 1968 (NT); in 1971; in August 1974 (NT) and September 1974 (NSW); and, finally, in August 1988 (NT pits only).

Rod movement in the plane of steepest slope was measured, using tapes and plumbline, to the nearest millimetre, the tip of the vertical rod acting as a reference mark for both vertical and horizontal components of movement. Tape readings were repeated by a second observer, where necessary, to ensure an accuracy of $\pm 0{\cdot}5$mm. Rods were inspected to check that they had not been disturbed and that the reference rod showed no obvious sign of displacement. Pits were back-filled to ensure close contact with the pit face containing the rods and overfilled so that settling would not lead to exposure of near-surface rods.

Williams (1973) reported results from 55 pits. In 1974, 54 pits were relocated of which 49 have produced data for our present study. The readings from several pits were rejected as we were not certain about the stability of the reference rods. A few uppermost rods were found to be disturbed; these have also been excluded from our analysis. Although some rusting of rod surfaces took place during the long period of interment, there was no obvious effect on measurement, as readings were referred to rod centres; rusting is likely to have been virtually symmetrical around the rods which had not become excessively thin.

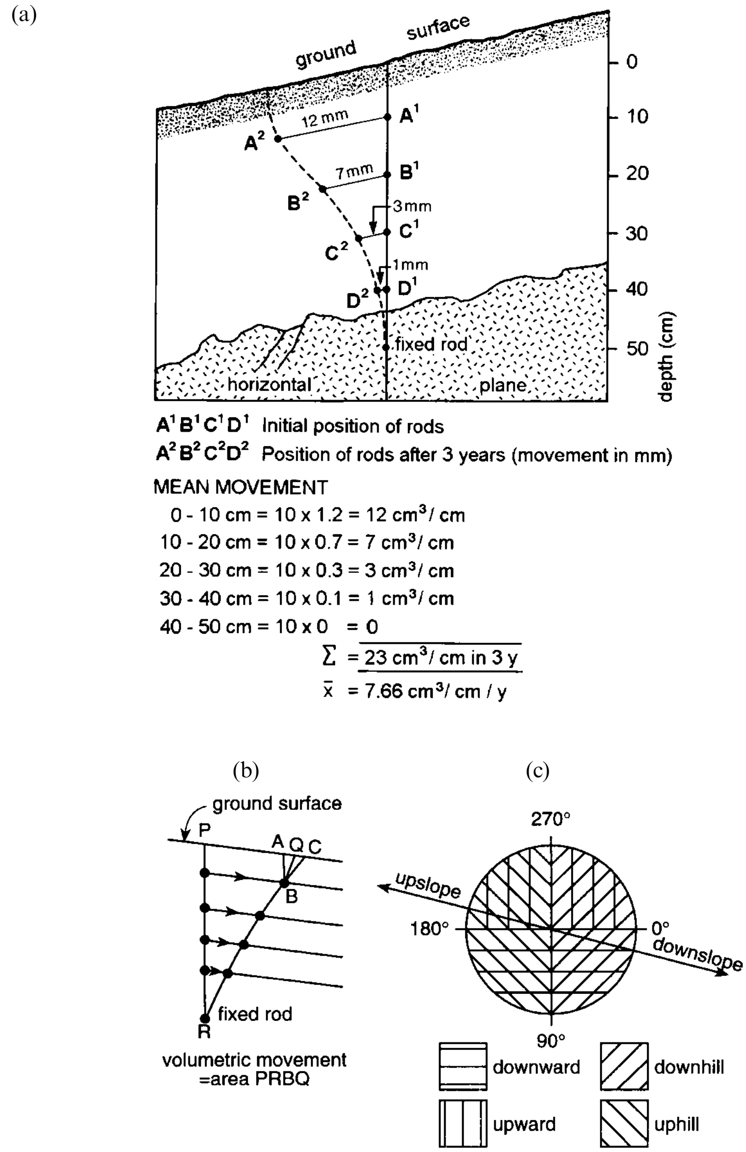

Figure 2. (a) Method of determining downslope volumetric creep from rod movement in a Young pit (After Williams (1975). (b) Key diagram for calculation of creep. (c) Orientation diagram lying in the plane of steepest slope for definition of terms used in the text

Calculation of creep rates

Volumetric creep rate is defined here as the volume of a 1 cm wide column of soil material moving past a given contour (Young, 1960). Calculation of volumetric creep rates in this paper differs from that reported by Williams (1969b, 1973). Williams estimated the volume of soil moved downslope by creep by multiplying the vertical interval between each rod by the amount of rod movement parallel to the surface. His calculations were obtained by summing the partial products of rod movement parallel to the surface and vertical distance to the rod or soil surface (Figure 2a). That method consistently underestimated the volume of soil displaced downslope. In this paper the creep rates are obtained from

the area enclosed by the creep profiles at the beginning and end of the period of investigation. The final creep profile is a curve, fitted by eye, passing through each rod position and intersecting the ground surface at point Q, as indicated schematically in Figure 2b, where BQ is the bisector of the angle ABC, and C is the point where the extrapolated creep profile intersects the ground surface. This extrapolation, giving a surface displacement PQ, is arbitrary but represents a reasonable compromise between the probable lower and upper limits of surface creep represented by PA and PC respectively. The maximum volumetric error incurred by this method of extrapolation is likely to be less than $0{\cdot}1\,cm^3\,cm^{-1}\,a^{-1}$ in all but six cases; for pits 7 and 8 (Table I) the error might exceed $0{\cdot}2\,cm^3\,cm^{-1}\,a^{-1}$.

We assume that the reference rods did not move during the period of investigation, but cannot be certain of this. Had there been movement, it would probably have possessed horizontal downhill and vertical downward components. In such circumstances the observed creep profile would be a truncated version of the full profile, the true point of zero motion being slightly further from the surface than, and upslope of, the observed position of the bottom rods. (In the event, our data showed that any possible movement of the bottom rods would, in the pits retained for analyses, have been insufficient to significantly affect the creep profiles.)

The intervals (in years) between observations in the NT differ from those in NSW and the total length of record are slightly different:-

	NT	NSW
1965–68	2·65	2·0
1968–74	6·1	6·65
1965–74	8·75	8·65
1974–88	14·05	–

All calculations involving rates of movement are based on actual time intervals. However, it is valid to compare NT and NSW data between 1965 and 1968 (hereafter, where convenient, termed before 1968), or between 1968 and 1974 (after 1968) as if time intervals were the same, because the NT pits were opened up in the dry season when the soils are extremely hard and dry and creep is likely to have been minimal. Consequently, had the NT intervals been the same as those for NSW, data would have differed little from those actually recorded.

Definition of directional terms used in this paper is given diagrammatically by Figure 2c.

RESULTS

Volumetric downslope movement of material

Data for each creep pit (1965 to 1974) are listed in Table IA where negative values indicate creep upslope. The creep rates are also displayed by locality in Figure 3 to show their distribution and in Figure 4 to show their relation to sine of slope angle. Both figures show that there is a substantial difference between the results for the NT granite and those of the other areas. The mean (and median) rates of creep for both sandstone areas and the NSW granite slopes are similar, whereas the rate for the NT granite area, in spite of its generally low slope, is over four times greater. Although one should not attach too much meaning to statistical analysis of abnormally distributed small sets of data such as these, there is a significant difference between the mean of the NT granite and the means of the NSW granite and sandstone creep rates at the 0·05 level, but none between any other pair of means.

If subsurface soil creep is related to slope gradient, we would expect this to be reflected in an association with the sine of slope angle, as the mechanical effect of gravity is proportional to this function of slope.

Williams (1974) reported measurements of 480 surface stones at 24 NT sandstone sites between October 1965 and December 1967. He found that the mean rate of *surface* stone creep (R) was directly

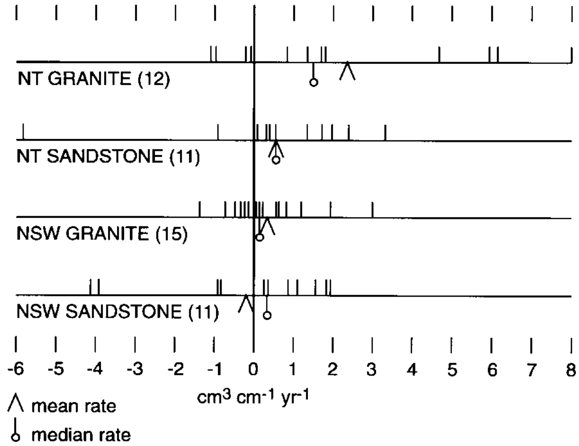

Figure 3. Distribution of creep rates, based on data in Table I. Brackets contain number of pits in each locality

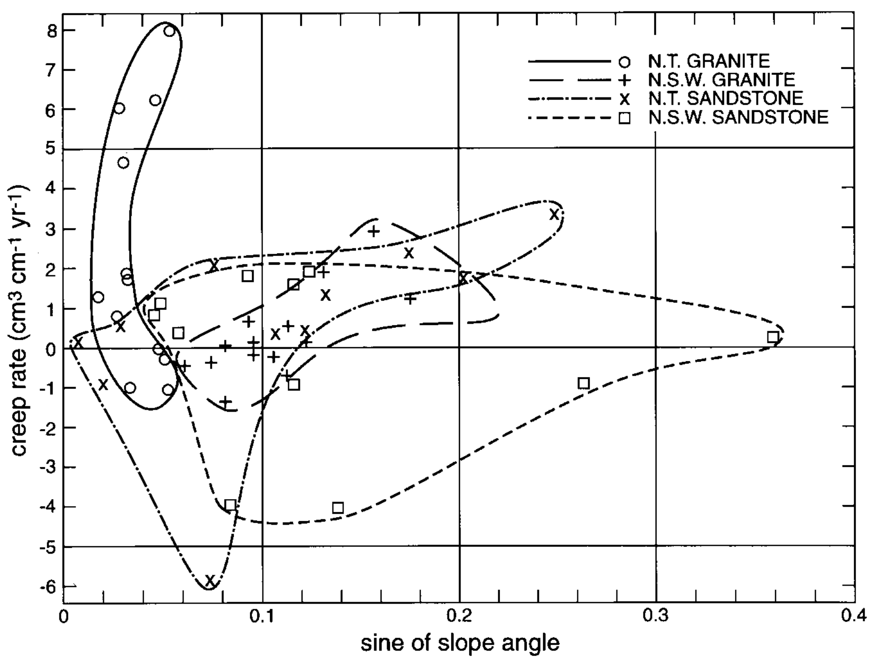

Figure 4. Relationship between creep rate and sine of slope angle

related to the sine of slope angle (sin A) according to the equation:

$$R = 10{\cdot}263 \sin A - 0{\cdot}109 \quad (1)$$

Figure 4 shows that any association between *subsurface* soil creep rate and sine of slope is weak, even if the large negative creep values are ignored. This is true both for the data as a whole and for data grouped according to locality. We are therefore unable to assert that slope angle alone is a significant

Table IA. Creep rates for 1965 to 1974 (in $cm^3\ cm^{-1}a^{-1}$) and other data for each pit, grouped by locality

NT				NSW			
Pit	**Slope**	**Sin S**	**Creep rate 1965–74**	**Pit**	Slope	**Sin S**	**Creep rate 1965–74**
1	1°40	0·029	4·64	60	4°40	0·081	0·08
2	1°50	0·032	1·66	61	6°00	0·105	–0·21
3	2°40	0·046	–0·33	62	5°20	0·093	0·67
4	2°55	0·051	–0·24	63	6°30	0·113	0·58
6	3°00	0·052	7·98	64	9°00	0·156	3·03
7	1°00	0·017	1·34	65	7°30	0·131	1·93
8	1°50	0·032	1·76	66	6°30	0·113	–0·72
9	1°50	0·032	–1·01	67	12°40	0·219	0·87
10	1°30	0·026	5·96	68	4°20	0·075	–0·33
11	2°35	0·045	6·15	69	3°30	0·061	–0·48
12	1°30	0·026	0·78	70A	10°00	0·174	1·22
13	3°00	0·052	–1·14	70B	5°30	0·096	0·14
				71	5°30	0·096	–0·14
				72	7°00	0·122	0·20
				73	4°40	0·081	–1·36
Mean rate	2.32			Mean rate	0.37		
Median rate	1.50			Median rate	0.14		
SANDSTONE				**SANDSTONE**			
20	11°35	0·201	1·75	40	4°50	0·084	–3·89
21	1°35	0·028	0·53	42	15°15	0·263	–0·87
23	4°15	0·074	–5·83	43	6°35	0·115	1·62
24	14°20	0·248	3·37	44	2°30	0·044	0·90
25	0°25	0·007	0·12	45	6°40	0·116	–0·82
26	10°00	0·174	2·40	48	7°55	0·138	–4·08
28	6°05	0·106	0·28	49	5°15	0·091	1·87
29	7°30	0·131	1·33	50	21°05	0·360	0·28
30	4°20	0·075	2·02	51	7°10	0·123	1·95
31	1°10	0·020	–0·90	53	2°45	0·048	1·17
32	7°00	0·122	0·41	54	3°15	0·057	0·40
Mean rate	0·50			Mean rate	–0·13		
Median rate	1·53			Median rate	0·43		

Negative values denote upslope movement
Pits 1–13, 60–73 are on granite; pits 20–32, 40–54 on sandstone.

factor affecting *subsurface* creep rates in our study areas.

In Table IB creep rates from 1965–88 may be compared with those from 1965–74 for those NT pits opened up in 1988. It is noticeable that, with one exception (pit 3), all rates are lower for the longer period and, on average, reduced by about 40 per cent in both granite and sandstone areas.

Further analysis of our data revealed that the pattern and amount of creep before 1968 differed markedly from that after 1968. Our measurements show that most of the slope-parallel creep had taken place by 1968 (Table IIA).

With the 23 year record of data we can compare the creep rates for 12 pits in the NT region, summarized in Table IIB, for the periods 1965–68, 1968–74 and 1974–88. The areal means declined markedly after the first period, with net rates directed upslope on the granite between 1968 and 1974. A further reduction in rates is evident after 1974, both granite and sandstone creep averages reversing in

Table IB. Creep rates for 1965 to 1974 and 1965 to 1988 (in $cm^3\ cm^{-1}a^{-1}$) for 12 NT pits

	NT granite			NT sandstone	
Pit	1965–74	1965–88	Pit	1965–74	1965–88
1	4.64	1.98	20	1.75	0.50
3	–0.33	0.47	21	0.53	–0.10
4	–0.24	0.10	26	2.40	0.84
8	1.76	0.77	28	0.28	0.23
9	–1.01	–0.21	29	1.33	0.51
			31	–0.90	–0.23
			32	0.41	0.19
Mean rates	1.02	0.62		0.83	0.28
Median rates	–0.24	0.47		0.53	0.25

Table IIA. Average creep rates (in $cm^3\ cm^{-1}\ a^{-1}$) for the periods 1965 to 1968 and 1968 to 1974

	1965–68 *a*	1968–74 *b*	*a*/*b*
NT, G	8·27	–0·27	30·6
NT, S	1·49	0·05	29·8
NSW, G	0·96	0·19	5·1
NSW, S	–1·51	0·28	5·4

G, granite; S, sandstone

Table IIB. Creep rates (in $cm^3\ cm^{-1}a^{-1}$) for 12 NT pits for each period 1965 to 1968, 1968 to 1974 and 1974 to 1988

	NT granite				NT sandstone		
Pit	1965–68	1968–74	1974–88	Pit	1965–68	1968–74	1974–88
1	14·16	0·51	0·32	20	2·52	1·42	–0·27
3	1·38	–0·64	0·73	21	–0·48	0·96	–0·48
4	2·54	–1·45	0·31	26	10·01	–0·91	–0·13
8	4·18	–6·10	0·16	28	4·48	–1·54	0·19
9	–2·44	0·71	0·28	29	3·04	0·58	-0·002
				31	–2·13	–0·37	0·19
				32	–0·24	0·70	0·05
Mean rates	3·96	–1·39	0·36	Mean rates	2·46	0·12	–0·06

direction. We have included the data for individual pits in Table IIB to show that there is a wide range of variation within the values that lead to areal averages. Such reversals of creep direction between the first and second periods were also characteristics of several other NT pits (three out of seven) and many NSW pits (10 out of 26).

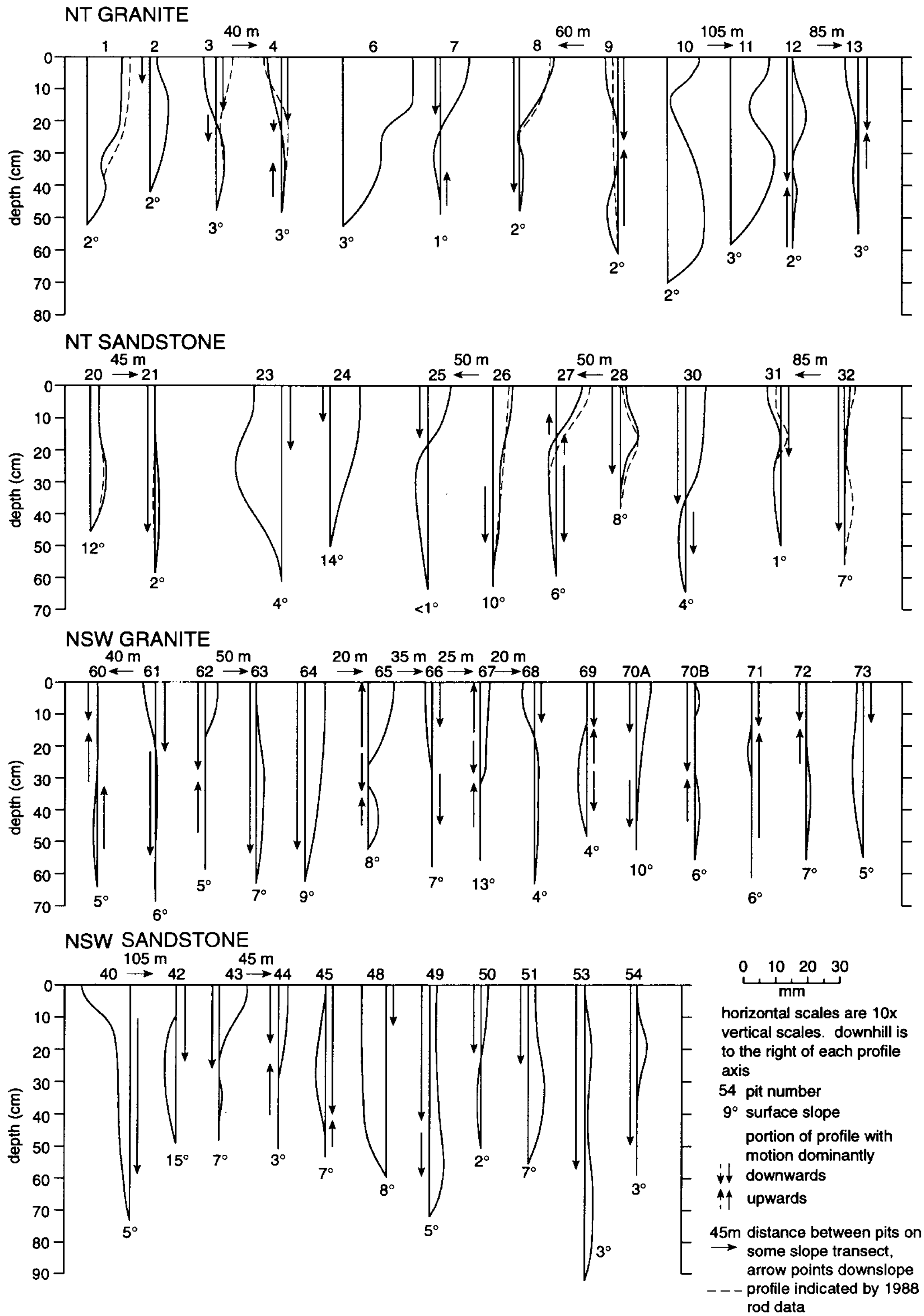

Figure 5. Creep profiles for each Young-pit, showing total movement during periods of 8·7 and 23 years

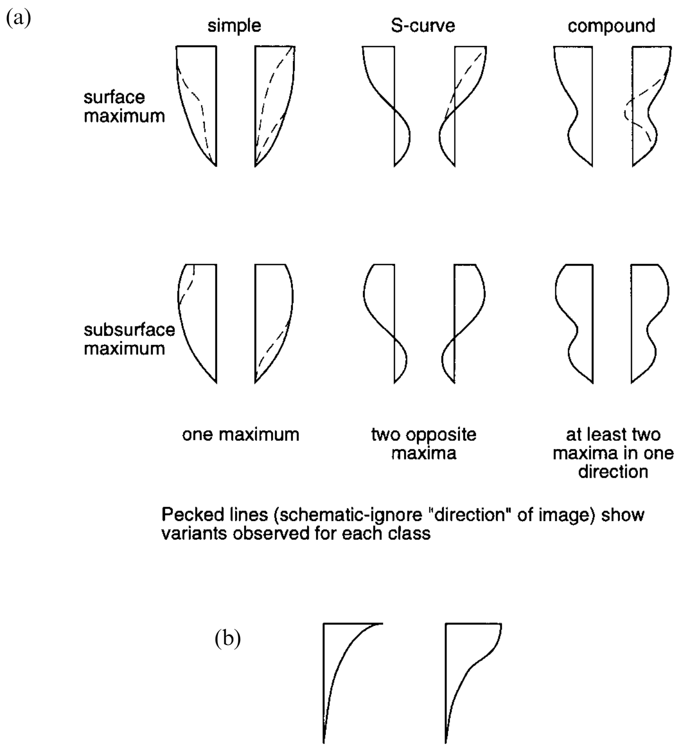

Figure 6. (a) A basic classification of creep profiles. (b) Theoretical creep profiles according to Kirkby (1967)

Creep profiles

The full set of profiles is displayed in Figure 5 where the horizontal exaggeration of scale is $\times 10$. They are grouped according to locality and, where two or more pits are located on a single slope transect, the linkage is shown by an arrow pointing downhill, with distances between pits given in metres. Surface slope is given to the nearest degree but, owing to the horizontal exaggeration of scale, the diagrams cannot show slope visually. What first strikes the eye is the great variety of profile shapes, a function of both amount and direction of movement. There are no obvious associations between profile shape and other observed characteristics of the environment. Apart from the fact that the NT granite profiles show, in general, rather more creep than those of the other three areas, and do so in spite of low slope gradients, there are no unambiguous associations between profile shape and lithology, gradient, profile depth, topography or local environment. Even where pits occur along the same transect, their creep profiles are, in most cases, dissimilar; the exceptions are the pairs 3 and 4, 10 and 11, 20 and 21. The sequence of profiles 64 to 68, in spite of being located along a single transect of only 100m, are all different from each other. Figure 6a depicts a basic classification of creep profiles, into which all of our 49 profiles may, as regards their essential visual characteristics, be fitted. It is interesting to note that only two of our profiles even approximate the theoretical profiles described by Kirkby (1967), illustrated as Figure 6b; in detail, neither of our profiles (Figure 5: 24, 70) conforms to theory. Moreover, no other profile would be similar to theoretical forms even if we had chosen to use the extrapolation BC instead of BQ defined in Figure 2b.

Table III groups our observed profiles according to the location of maximum creep and shows that, for the most part, the maximum value of creep, whether up- or downslope, is at the ground surface.

Table III. Pit profiles classified according to the scheme illustrated in Figure 6

	Surface maximum	Subsurface maximum	Simple	S-curve	Compound
NT, G	10	2	1	3	8
NT, S	7	4	6	3	2
NSW, G	9	6	10	3	2
NSW, S	4	7	7	1	3
Total 49	30	19	24	10	15

G, granite; S, sandstone

Table IV. Pit profiles classified according to dominance of vertical component of movement using data for 1965 to 1974

	Vertical component dominant in most of profile		Vertical component dominant in less than half of profile		Vertical component not dominant in any part of the profile
	Downward only	Part downward, part upward	Downward only	Part downward, part upward	
NT, G	1	5	2	0	4
NT, S	4	1	5	0	1
NSW, G	5	7	2	1	0
NSW, S	5	2	4	0	0
Total 49	15	15	13	1	5

G, granite; S, sandstone

However, subsurface maxima are not rare; they occur in all areas and at various depths between 15 and 75cm from the surface. There is a marked dominance of simple profile forms except on the NT granites. Six of the seven compound granite profiles were obtained from one of two low hills in this locality; the other hill produced four simple, one transitional and one compound type, a balance between simple and compound forms similar to that in the other field areas. The difference between profiles on the two hills does not seem explicable in terms of local lithological or pedological characteristics. The only environmental features associated with the difference are aspect and growth of vegetation. Slopes where compound profiles are dominant face SW, S and SE, supporting taller woodland than the NW, N and NE facing slopes on which simple profiles are found.

Vectorial motion of rods and direction of creep

It had been apparent in 1968 (Williams, 1969b) that movement of most rods in the Young-pits was not parallel to ground surface and that, in many cases, there was a greater component normal to the surface than parallel to it. However, discussion of data at that time was solely in terms of movement parallel to the surface slope. Further observations at all sites in 1971 again revealed that vectorial motion of rods was usually far from parallel to the ground surface and this was confirmed by data collected in 1974 and 1988. It became obvious that such motion was not spurious but persistent, and could not be ignored as if it were a transient phenomenon.

In Figure 5, those portions of each profile where the vertical component of motion appears to be dominant are emphasized by vertical arrows and entail the following assumptions: firstly, that the rods have not moved relative to the surrounding soil (a point that we shall later criticize); secondly, that the

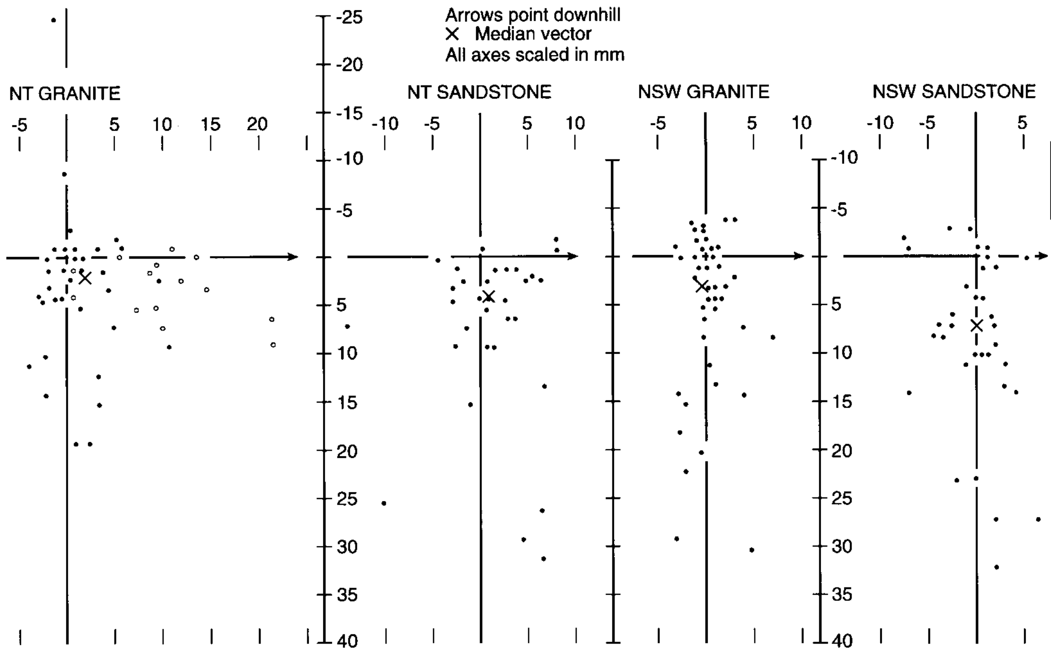

Figure 7. Vectorial movement of rods, in the vertical plane oriented as illustrated by Figure 2c, during the study period 1965 to 1974, by locality. Rods in pits 6, 10 and 11 are indicated by open circles

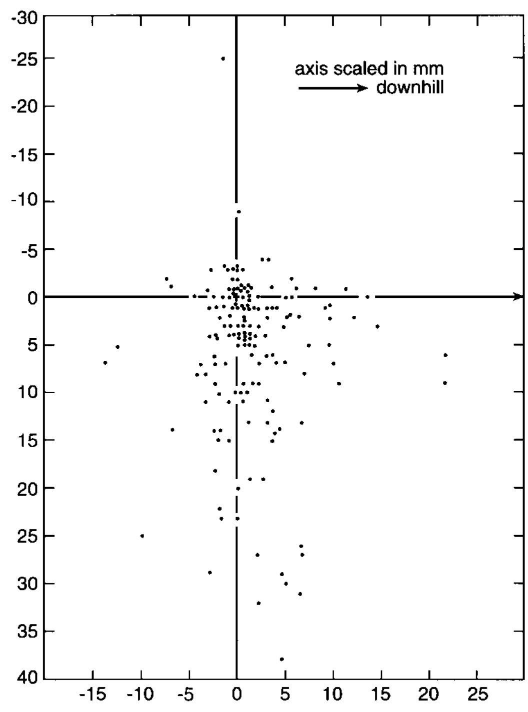

Figure 8. Vectorial movement of rods 1965 to 1974; data as for Figure 7 but plotted on one diagram

Table V. Direction of rod movement in place of steepest slope, 1965 to 1974. Number of rods in each category

	Downward and downhill			Downward and uphill			Upward and uphill			Upward and downhill		
	0–29°	30–59°	60–89°	90–119°	120–149°	150–179°	180–209°	210–239°	240–269°	270–299°	300–329°	330–359°
NT, G	13	7	8	7	2	0	1	2	1	4	0	4
NT, S	5	3	10	5	3	2	1	0	0	1	0	2
NSW, G	2	4	10	13	0	0	3	0	3	6	3	0
NSW, S	3	0	12	12	1	1	2	1	1	1	1	0
Total 150	24	13	40	27	6	3	7	3	5	12	4	6

G, granite; S, sandstone
Refer to Figure 2b for orientation

Table VI. Direction of rod movement in relation to the ground surface, 1965 to 1974

	Downslope*	Downhill towards surface	Away from surface	Upslope*	Uphill towards surface	Away from surface
NT, G	9	7	20	1	3	9
NT, S	4	3	14	1	0	10
NSW, G	2	9	14	2	4	13
NSW, S	2	2	13	2	2	14
Total 150	17	21	61	6	9	36

* Downslope and upslope are parallel to the surface $\pm 10^\circ$
G, granite; S, sandstone

motion of soil between rods is similar in general direction to that of the nearest rod, this being the simplest assumption consistent with the data and adequate for our present purpose. That the vertical component of motion dominates the horizontal in most pits is quite evident. Table IV summarizes the profile data, revealing that in 30 of 49 pits the vertical component is dominant in most of the profile, whereas in only five of the pits is the horizontal component dominant throughout the profile. The diagrams and table both show that the downward component of motion is considerably more significant than the upward component which is, however, not negligible. Although the pit data have been grouped according to locality, the sample size per locality is too small to support statistical tests for areal differences between the components of creep.

The two-dimensional vectorial motion of individual rods for 1965 to 1974 is shown in Figures 7 and 8, and summarized as regards direction of motion in Table V. Again, the dominance of the vertical component of motion is obvious. In the NSW granite and both sandstone areas the median vectorial motion is close to being vertically downwards, the greatest vectorial magnitudes of movement lying in the sector 60° to 120° (see orientation diagram, Figure 2c). The NT granite area produced a somewhat different pattern of rod movement (Figure 7), there being a relatively greater number of rods with vectorial motion in the sector 331° to 60° with a median vectorial motion close to 45°. However, this difference can be ascribed to the motion of rods in three pits (pits 6, 10, 11: open circles in Figure 7); without their contribution the NT granite pattern would be very similar to that of the other areas, with its median vector close to vertically downwards. Ignoring the contribution of rods in pits 6, 10 and 11, the distribution of vectorial movement in the NT areas for the period 1965 to 1988 resembles the patterns displayed in Figure 7. The median vector for the granite sites remains close to the 1965 to 1974 position, but that for the sandstones is displaced downwards to 9mm, emphasizing the significance of the vertical component of movement.

Table VI shows that in each area a minority of rods moves either up- or downslope; most rods move

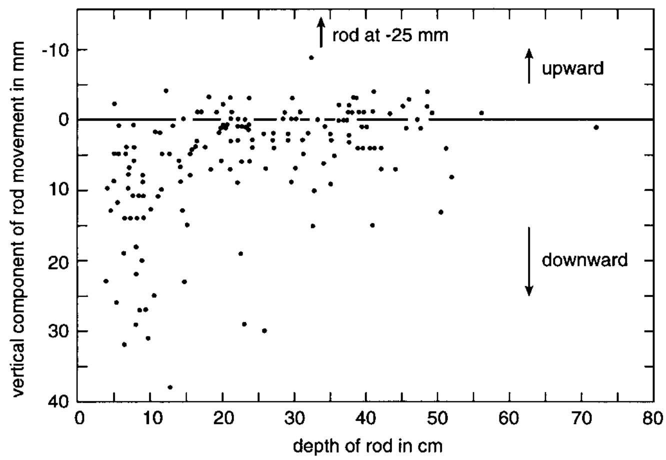

Figure 9. Vertical component of rod movement during the study period 1965 to 1974 plotted against initial depth of rod

away from the ground surface. In fact, of the 150 rods for which we have reliable measurements, the vertical component of motion is dominant in 110 cases, this dominance being characteristic of all four localities. A plot of vertical component against depth for each rod is depicted in Figure 9. This reveals some tendency for the vertical component to decrease with depth from the ground surface. In general, the horizontal component also decreases with depth. However, there is negligible correlation between the magnitudes of the components (correlation coefficient = 0·02), which implies that the surface-parallel component of motion conventionally assumed for the calculation of creep rates is, likewise, uncorrelated with actual vectorial movement.

At this stage in our analysis it became apparent that the commonly accepted view of creep as a movement of soil or regolith roughly parallel to the slope of the land surface is merely to abstract the slope-parallel component of an actual motion which, in most instances and on average, is in some other direction, frequently uphill, and usually downward. Consequently, the visual impression of slope-parallel motion given by the typical creep profile gives a misleading indication of displacements within the solum. This has been illustrated by Young (1978) who plotted the vectorial movement of rods in a soil pit after 12 years; even on a relatively steep slope (28°) his vectorial rod movements were generally closer to vertically downward than slope-parallel. Likewise, Moeyersons (1988), investigating an area of steep slopes in Southern Rwanda over consecutive three year periods, found that many of his tracers indicated vectorial movements which were far from slope-parallel. Similar examples from pits in our areas are portrayed in Figure 10. It can be seen that, whereas in some pits rods move with similar orientation, in others rods move in a variety of directions.

Temporal incidence of maximum and minimum recorded movement

So far, our data have been analysed in terms of gross rod movement over the whole period 1965 to 1974 or 1965 to 1988 and, in common with previous studies of creep, we had been concerned with measuring creep over as long a period as possible, in order to obtain accurate data minimally affected by errors of measurement which may be relatively large for short periods of observation. However, perusal of the data collected for the same set of pits in 1968 (and 1971, not presented in this paper) indicated that most of the rod movement, and hence 'creep', had occurred within the first three years of the study. Consequently, we undertook a more detailed analysis of the 1968 data with the following interesting (and cautionary) results.

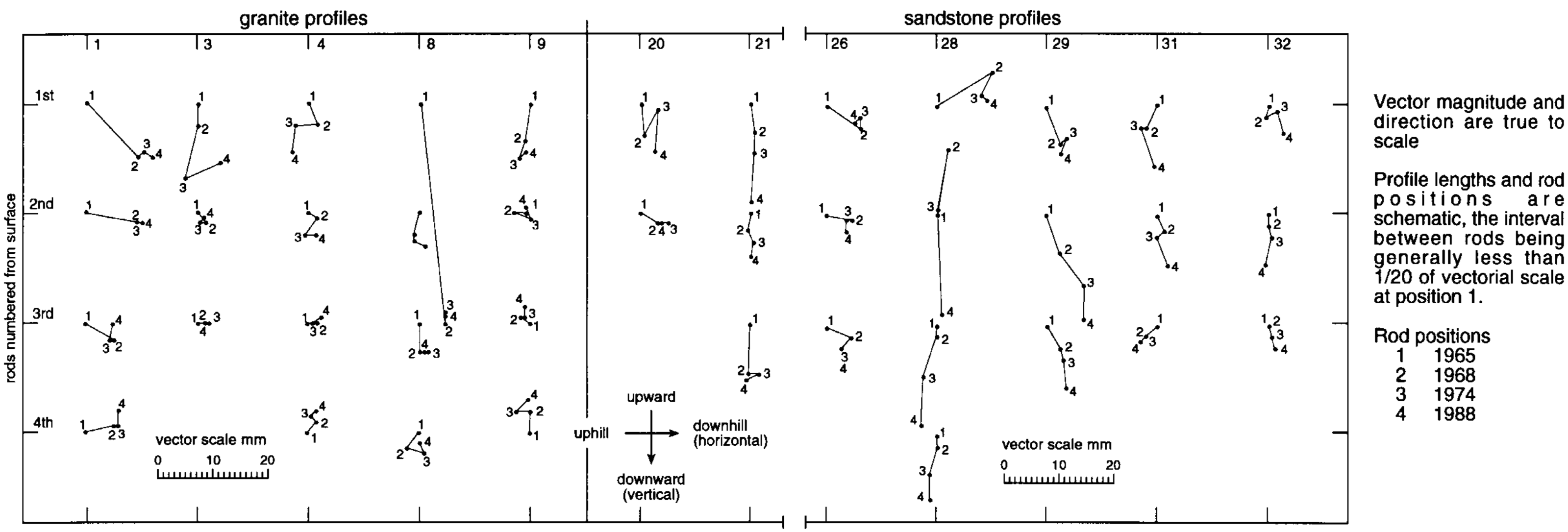

Figure 10. Vectors of rod movement for NT pits opened in 1988

Table VII. Total length (in mm) of vectorial rod movement, averaged by locality for the periods 1965 to 1968, 1968 to 1974 and 1965 to 1974

	1 1965–68 ***a***	2 1968–74 ***b***	3 1965–74 ***a+b***	4 1965–74 ***c***	5 $\frac{a}{a+b}$	6 $\frac{a}{c}$	7 $\frac{a+b}{c}$
NT, G	7·85	3·45	11·30	8·88	0·69	0·88	1·27
NT,	6·43	4·83	11·26	9·09	0·57	0·71	1·24
NSW, G	5·75	2·91	8·66	6·88	0·66	0·79	1·26
NSW, S	8·25	4·04	12·29	10·01	0·67	0·82	1·24
All rods	7·08	3·71	10·79	8·62	0·66	0·82	1·25

G, granite; S, sandstone

Table VIII. Rate of vectorial movement (in mm a^{-1}) averaged by locality for the periods 1965 to 1968, 1968 to 1974 to 1988

	1965–68 x	1968–74 y	$\frac{x}{y}$	1968–74 y^*	1974–88 z	$\frac{y^*}{z}$
NT, G	2·96	0·57	5·2	0·37	0·15	0·41
NT, S	2·43	0·79	3·1	0·53	0·34	0·64
NSW, G	2·87	0·44	6·5			
NSW, S	4·12	0·61	6·8			

* y values for pits opened in 1988
G, granite; S, sandstone

Firstly, it appears that, on average and in all areas, most of the rod movement observed in 1974 had taken place during the period 1965 to 1968. The average displacement by 1968 was apparently 82 per cent of that recorded in 1974, although there was some minor variation between areas (Table VII, column 6). However, most of the rods did not move in a constant direction during the nine year period. Table VII indicates that, for the four areas and for all rods taken together, the vectorial displacements before 1968 and after 1968 (vectors $\boldsymbol{a} + \boldsymbol{b}$) are consistently about 25 per cent greater than vector $\boldsymbol{c}$ obtained solely from the 1965 and 1974 data (Table VII, column 7). Even so, the period before 1968 still accounts for some two-thirds of the total movement (column 5). Consequently, the average annual rates of rod displacement during the first period are from three to nearly seven times those of the second period (Table VIII). The very marked decreases in rod movement during the second period cannot adequately be explained by a change in environmental conditions.

To avoid undue complexity we have not displayed data for 1965 to 1988 in Table VII. Suffice it to say that the pre- and post-1968 contrast is reinforced by the longer-period data, particularly in the NT sandstone area. As indicated by Table VIII, there is a further significant decrease in the rate of vectorial movement after 1974, by 60 per cent on the granites and 36 per cent on the sandstones.

The pattern of rod movement during the two periods is illustrated in Figure 11. The pattern before 1968 is somewhat similar to that for 1965 to 1974 (Figure 8), but less dispersed from the origin of coordinates. After 1968, however, the pattern is much more concentrated about the origin. During both periods the vertical component of motion dominates the horizontal. Patterns for the separate localities during each period resemble those illustrated in Figure 7 and call for no special comment. Although the pattern of rod movement after 1974 is only based on a selection of NT rods, the scatter of points, weighted by 0·43 to take into account the difference in length of time-interval, is noticeably less than the scatter for the period 1968 to 1974. It is worth pointing out that, whereas none of the sandstone rods moved upwards during this final period, an upward component is present in the majority of granite

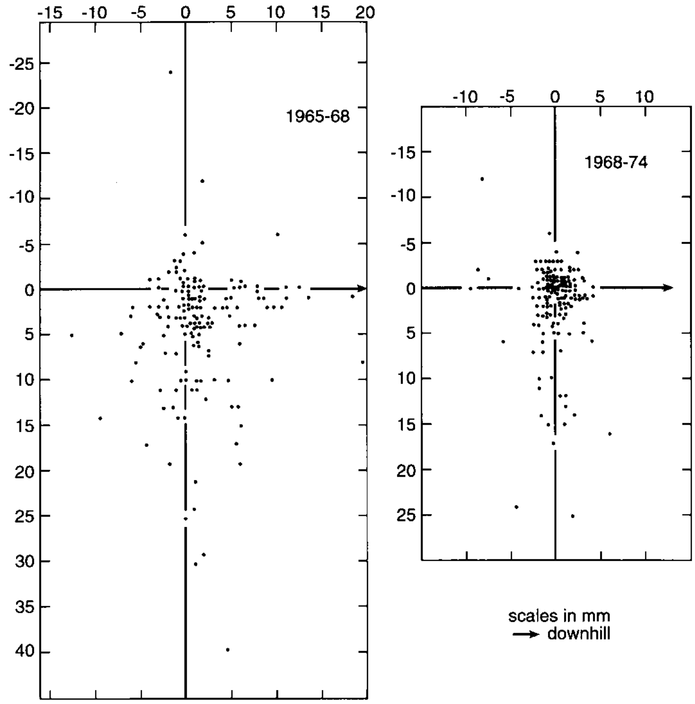

Figure 11. Vectorial movement of rods during the periods 1965 to 1968 and 1968 to 1974 (compare with Figure 8)

vectors (Figure 12). The detailed picture of these rod vectors throughout the study period has been used as the basis for Figure 10.

That the movement of rods did not remain constant in direction during the nine year period of observation has already been noted. Table IX summarizes the apparent changes in direction from pre-1968 to post-1968. After 1968 only 44 of the 160 rods continued to move in roughly the same direction as before 1968, while nearly half of the rods changed direction by more than 90°, several virtually reversing their direction of movement. Such reversal of motion was not negligible; in one instance (pit 28, rod 2), a rod moved 12mm in one direction and 11mm and nearly 180° back, to finish, in 1974, only 1mm from its origin in 1965. After 1974 few rods continued to move in the same direction; about half of their vectors changed by at least 60°. It seems likely that, were it possible to record annual vectors accurately, the patterns of rod motion would be even more irregular. Such details would permit a better analysis of movements than is at present possible using apparent vectors obtained from our occasional observations. The rod vectors depicted in Figure 10 do not support the concept of soil creep as a dominantly downslope and slope-parallel process.

DISCUSSION

Rod movement relative to the soil

For our presentation of results, having omitted from analysis any data dependent upon rods which may have been disturbed or were not referrable to an apparently fixed reference rod, we have assumed no movement of rods with respect to the soil that immediately surrounds them. However, the possibility that such relative motion did occur, but was not obvious to the naked eye, merits comment.

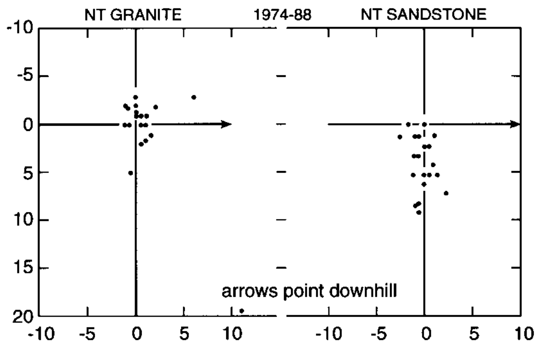

Figure 12. Vectorial movement of NT rods between 1974 and 1988

Table IX. Angular change in direction of rod movement between the periods 1965 to 1968 and 1968 to 1974

	0–30°	30.1–60°	60.1–90°	90.1–120°	120.1–150°	150.1–180°	Indeterminate*
NT, G	13	6	5	8	9	7	1
NT, S	10	4	3	4	6	3	2
NSW, G	6	5	9	8	5	9	2
NSW, S	9	2	6	1	7	7	3
Total 160	38	17	23	21	27	26	8

* No movement
G, granite; S, Sandstone

A rod could show abnormal displacement if tree roots impinged upon it in the soil. Since only the tips of rods are exposed in the pit face, we would not be able to observe such a process. Displacements could be in any direction, perhaps producing apparent uphill or upward motion. Most of our pits were in forest (NSW) or open woodland (NT). However, we have little evidence of major root penetration of the exposed pit walls and infer that few rods were likely to have suffered displacement by root growth. It also seems unlikely that during the opening and closing of pits there was any accidental disturbance of rods, nor does it seem likely that the relatively unconsolidated fill in the pits would produce rod movement in the plane of measurement (parallel to ground slope). If there were differential movement of soil along the horizontal length of the rod, over time the rod displacement should reflect the resultant of all such movement, hence the need for long-term monitoring.

The insertion of rods at the beginning of the experimental period must have compressed surrounding soil to a radial distance of several millimetres. Whether or not such compression is progressively relieved and, if it is, whether or not the relief is radially symmetric we do not know. So far as we are aware, no research into this problem as it affects isolated rods has been undertaken, but differential creep due to relief of the stresses set up by rod insertion cannot be ruled out. It may account for some, though not all, of the relatively rapid creep observed during the early period of our study.

Since the rods used in our pits were steel and, therefore, much denser than the surrounding soil material, one might suppose that they could settle vertically into it. Calculations based on the method of determining stress distribution beneath foundations, originated by Boussinesq (1885) and discussed by Reynolds and Protopapadakis (1959), show that the maximum stress exerted by our rods on underlying soil is approximately 520 N m^{-2}. This is an order of magnitude below the shearing strength of a wet pure

clay. Our soil materials were loams, clay loams and coarse sandy soils, all of much greater strength than moist clay, so that settling of rods under their own weight is extremely unlikely, even in wet seasons.

In the course of short-period observations for a doctoral thesis, Humphreys (1985) found that several of his Young-pit rods were displaced downwards and apparently disturbed by root growth. However, Humphreys' aluminium rods were very thin (2mm) and may have been insufficiently rigid to resist deformation during insertion or exhumation.

To conclude this discussion of rod movement relative to the soil, it is worth noting that, even if there were small undetected movements of the basal reference rod, it is most unlikely that the resultant motion of the reference tip would be other than close to horizontal, so that the errors in observation would be small horizontal quantities having little significance for our conclusions.

Estimation of average annual soil movement

Our analysis has shown that rod movements before the opening of pits in 1968 were considerably greater than thereafter (Table VIII). It is conceivable that most of the pre-1968 movement took place within the first year (or rainy season) of the study. Average rates of precipitation before 1968 were not significantly different from those after 1968, so that soils would not have been more frequently saturated in the earlier period. Nor can extreme rainfall events be invoked as a plausible explanation of the high initial creep rates. The recurrence interval of tropical cyclones in the NT study areas is one year in two (Williams, 1969a), so that high intensity summer rains are the norm rather than the exception. Rainfall intensity in the uniform rainfall NSW sites is always low relative to the NT sites, and the shallow depth of penetration of freeze–thaw cycles in winter rules out frost as a major causal factor. The difference between pre- and post-1968 creep rates is too great to be explained by invoking temporal differences in precipitation and soil moisture conditions, for which we have no evidence. We are thus led to suggest that some adjustment of the soil to the initial insertion of rods may have occurred during the early stages of this study.

Therefore, the overall average rates of movement between 1965 and 1974 may be misleadingly high. Perhaps the 1968–74 averages are more representative of long-term motions; the even lower 1974–88 averages for pits examined after a further 14 years support this suggestion. These remarks apply equally to the creep rates given in Table II. If our observations are valid, then the question is raised: are any creep rates obtained from a short period of measurement, or for which the first few years of movement are taken into account, representative of longer term rates? Likewise, the reversal of creep direction after 1974 for two-thirds of the pits opened in 1988 indicates that medium-term averages may also be unrepresentative.

The nature and causes of soil creep

Our analysis of the vectorial motion of rods indicates that conventional measurement of soil-creep as motion parallel to the ground surface often bears little relation to the magnitude and direction of actual motion with the soil. In fact, the majority of rods in our pits were moving away from or towards the ground surface rather than parallel to it; even taking pits as a whole, the vertical component of motion, usually downward, dominates the horizontal (or slope-parallel) component.

Young (1978) found that mean vectorial motion in a pit opened after 12 years was 14° away from vertical and that some individual rods had moved somewhat upslope of vertically downward. Although some of the vectorial motion of rods may be a consequence of stresses induced by insertion of the rods, we agree with Young that such motion largely reflects natural soil creep. However, the explanation cannot be simple. Not only do we have to account for a vertically downward component of creep (applicable to Young's observations), but for upward and uphill motions, as well as contradictory motions within several pits.

Young suggests loss of material in solution as the reason for his observations, such solution causing

both loss of soil volume and rearrangement of particles. The component of creep normal to the surface and part of the downslope component are thereby explained, the rate of solution loss increasing towards the surface (his creep profiles have a maximum creep rate at the surface). To what extent our rod movements could be explained in similar terms is an open question. Some pits (e.g. 64, 70A) produced simple profiles for which Young's suggestions may be appropriate, but to explain others – those with maximum creep in subsurface layers, with uphill or upward creep, or compound profiles – would presuppose spatially complex solutional processes for which we have no theoretical models or experimental evidence at present.

As regards compound profiles, Lewis (1976) found that relatively wet soils under rainforest vegetation in Puerto Rico exhibit profiles with a double maximum of creep (one at the surface) suggesting that this phenomenon was caused by maximum flow along shearing zones when soil strength is reduced. Where similar profiles occur in our areas, there is no obvious reason to draw such an inference. No evidence for mass flow was revealed by our soil pits; furthermore, the dominance of the vertical component in several profiles with subsurface maxima is not compatible with any simple form of mass flow along shearing zones parallel to the ground surface.

The pattern of creep in a large Young-pit containing a grid of tracer lines is described and discussed by Moeyersons (1988). From the tracer point-observations, he constructs patterns of 'creep lines' (cf. flow lines in a fluid, along which any element is a vector), which seem to indicate soil movement converging towards a relatively porous horizon of low unconfined strength lying between an upper humic horizon and a more cohesive subsoil. Unfortunately, it appears that there is no point in the network of tracer lines fixed with respect to the bedrock substrate, so that the actual pattern of creep lines derived from the tracer observations could be markedly different from the apparent vector fields depicted by Moeyersons.

The notion that soil movement, including so-called creep, produces a fluid-like pattern of flow lines – even 'turbulent flow' in the subsoil (unless the solum is lubricated by the presence of sufficient water in a clay matrix) – seems far-fetched to us; and we cannot interpret our pit profiles in the context of a flow field. It appears likely that there are alternative explanations for the structural characteristics of Moeyersons' soil profiles (especially his 'intermediate horizon'), bearing in mind (a) the steepness of the slopes coupled with obvious signs of mass-movement along shear surfaces within the upper soil horizons, and (b) the role of bioturbation in tropical soils and its impact on topsoil mobility (Paton, 1978; Paton *et al.*, 1995).

The role of bioturbation

Upward, upslope, and some downward or downslope creep could be due to the growth (and decay?) of small roots, insufficient in size to displace rods with respect to the soil, but able to create volumetric changes in the soil itself. Although long-term creep in the presence of root growth and decay would tend to be downhill under the overall influence of gravity, creep in other directions is quite conceivable in the short run, even for several decades. We have no evidence in our field areas either for or against this possibility but are certain that it should not be ignored in the presence of trees, shrubs or grasses with extensive root systems. However, neither the overall downward tendency of creep, nor the primary characteristics of our profiles, can be ascribed to volumetric changes due to root growth.

Williams (1973) suggested that the higher average creep rates on the NT granite slopes may be a consequence of disturbance by the considerable activity of mound-building termites. As noted earlier, the three-layered M/S/W granite soil profiles are entirely consistent with sustained termite activity (Williams, 1968, 1978a), but we lack direct evidence that termites have affected the pit sites themselves during the period of creep investigation.

As both M and S layers extend downslope of near-surface granite, they appear to be relatively mobile (though possibly only with respect to time-spans greatly in excess of our period of study), whereas the W layer with its relict granite fabric shows little sign of downhill movement. Williams (1968) estimated that,

on average, termite activity lowers the surface of the W layer by 0·07mm a^{-1}. Lowering of the surface of the W layer by 0·07mm a^{-1} would only account for one-third of average vertical downward motion between 1968 and 1974 and less than one-eighth of such motion during the full period of observation. Consequently, even if termite activity contributes towards creep, it seems unlikely to be the prime cause.

Other small fauna, in particular earthworms and ants, also extract material from within the soil and add it to the surface. In sandstone areas around Sydney these fauna are apparently capable of annually recycling soil material equivalent to a layer 0·7mm thick (G. S. Humphreys, 1983, pers. comm.). Mitchell (1988) also discusses the relevance of bioturbation to soil processes with particular reference to faunal activity in texture-contrast soils of eastern New South Wales. Annual recycling rates in areas examined by him and his colleagues appear to be no greater than 0·1mm a^{-1} on average, although local variations in short periods could be considerable. It is now known that active turnover of soil material affects topsoil in texture-contrast profiles and may affect gradational profiles to considerable depths (Paton *et al.*, 1995). Quantitative extrapolation from the NSW sites described by Mitchell is not warranted; however, the maximum rates of turnover calculated for those areas could only account for a small fraction of all but a few rod displacements in our soil pits. (Nevertheless, since we do not know with certainty that rod motions are reliable indicators of soil movement, we do not wish to imply that bioturbation is of little significance.)

The role of climate

The influence of climate on soil movement in our field areas is hard to determine. Expansion and contraction of soil due to alternate wetting and drying is seasonal in the Northern Territory; it is irregular and possibly more frequent in the Southern Tablelands of New South Wales. Freeze–thaw sequences may affect the top few centimetres of soils in the Southern Tablelands but do not occur in the Northern Territory. The effect of alternate expansion and contraction of soil is to produce net movement downslope, paralled to the surface, according to the investigations of Davison (1889), Owens (1969), Barr and Swanston (1970) and Young (1972). In the terms suggested by these authors, the influence of climate via these mechanical activities can only be a minor factor influencing soil movement in our areas, as they do not account for the dominant vertical component of motion. In a study of vertical movement of ground due to changes in soil moisture over a period of three years including the very dry summer of 1949 in eastern England, Ward (1953) notes that vertical displacements of up to 20mm occurred to a depth of 0·9m under grass and 10mm to a depth of 0·3m under bare soil. Where trees were present, the evapo-transpirative effects could extend to a radius exceeding 10m. Such magnitudes of movements would certainly need to be taken into account if, as is likely, they are characteristics of the markedly seasonal moisture regime of our NT sites and of NSW sites during drought conditions. However, until we know considerably more about the results of repeated contraction and expansion in a wide range of soil types, any further comment about soil-moisture variations and net movement within a profile will be purely conjectural. Likewise, climatic effects on movement via solution and leaching of soil material can only be surmised, given our present state of knowledge.

Finally, it is not possible to explain our observations of soil movement in terms of the various theoretical models of creep (Culling, 1963, 1965; Souchez, 1963; Kirkby, 1967) as each theory presupposes that soil creeps parallel to the ground surface.

This discussion leads to the conclusion that we are not at present able to relate soil creep in our areas to any specific cause or set of causes, even though we can identify several possible general influences.

Implications for the measurement of soil creep

Several methods of measuring soil creep have been developed during the last four decades: surface pegs (Young, 1960; Rapp, 1962); tilt bars (Kirkby, 1967); buried pressure-plates (Everett, 1963), superposed cylinders (Rudberg, 1958) or cones (Selby, 1968); deformation of tubes using strain-gauges

(P. J. Williams, 1957; Barr and Swanston, 1970), inclinometers (Kallstenius and Bergau, 1961) or optical observations (Finlayson and Osmaston, 1977; Finlayson, 1981); and Young-pits (Young, 1960). Although Finlayson's technique permits the magnitude and direction of creep to be obtained in a plane that is parallel to the ground surface, none of these methods, with the exception of Young-pits, is suitable for measurement of vertical soil movement. Consequently, only Young-pits can provide evidence for motions away from, or towards, the ground surface. Since our research and that of Young (1978) indicate that merely slope-parallel observations of creep are inadequate, Young-pits, in spite of their drawbacks, should continue to be used for the measurement of creep until such time as a more efficient technique for obtaining data in a vertical plane (or, better, in three dimensions) is devised.

Culling (1983a) discusses the interesting possibility of using steady-state distributions to measure transport (creep) rates. The basis of his method is a model of creep as a downslope drift operating in conjunction with randomly orientated diffusion of a particulate medium. Although Culling's (1983a, b, c) statistical theories may be testable in laboratory conditions for specific aggregates, adequate tests in the field are, given the complexity of soils and the present lack of suitable instrumentation, difficult to envisage. However, if the drift of soil particles is not necessarily downslope but possesses a significant, possibly dominant, vertically downward component, Culling's method will either have to take into account the likelihood that the direction of drift cannot be assumed but must be predetermined, or be adaptable for the initial condition that drift direction is unknown.

Overall implications for soil creep process mechanisms

We have discussed a number of possible models and mechanisms of soil creep. These include: (a) movement downslope en masse under the direct influence of gravity; (b) shear failure along shear planes roughly parallel to the surface at scales ranging from microsopic to macroscopic; (c) bioturbation (burrows, roots, mound casts); (d) vertical and lateral eluviation and illuviation; (e) solution processes; (f) random particle diffusion under gravity, resulting in density layering in the soil; (g) turbulent flow within the soil. Soil creep may stem from any of these processes. Only in the case of (a) and (b) can we be reasonably confident that the rods reflect actual soil movement; in the other cases we cannot exclude differential movement of soil past each rod. It seems highly likely that the range and complexity of velocity profiles seen in our study reflect the complex interactions of a wide range of subsurface transport processes, all of them subsumed under the disarmingly simple term 'soil creep'. It seems that the search for a simple unicausal model of creep is chimerical.

CONCLUSIONS

From this study our main conclusions are as follows.

(1) Soil creep, considered solely as a slope-parallel process, takes place at rates varying from $+7{\cdot}98$ to $-5{\cdot}83\,cm^3\,cm^{-1}\,a^{-1}$, showing no systematic relationship to sine of slope angle, nor to any other readily observable soil or climatic characteristic.
(2) It is no longer valid to regard creep solely in terms of displacement parallel to the ground surface; most of our observations indicate a dominant vertically downward component in the creep vector.
(3) Over periods of nine and 23 years creep was frequently uphill and upward. If such movement is eccentric, a much longer period is required in order to establish the long-term direction of creep.
(4) Most of the rod movement in our pits occurred within the first two to three years of the experimental period. This suggests that adjustment of the soil to forces exerted by insertion of rods may have taken place. Consequently, the average creep rates of undisturbed soil may well be overestimated.
(5) The actual causes of creep remain obscure. Several possible causes have been proposed but none satisfactorily explains our observations, although, since a loss of soil volume is indicated by the downward component of rod movement, chemical or physical removal of material may be an important factor.

(6) Among the various methods of observing soil creep, Young-pits remain most suitable for obtaining measurements of soil movement that is not parallel to the ground surface.
(7) In spite of the numerous investigations that have been undertaken in the past 30 years, the study of soil creep is still in its infancy. Further progress will depend on patient, long-term and ideally continuous field observations not only of soil movement itself, but also of likely associated phenomena such as the activity of soil fauna, soil moisture conditions and chemical activity, together with fabric analysis. Laboratory experiments are also needed, particularly concerning the adjustment of soil to disturbance by implanted objects such as rods.
(8) Finally, we suggest that, in the light of our investigations, the usual definition of soil creep, which emphasizes movement parallel to the surface slope, is inadequate and shown to be quite unrealistic by the vectorial movements illustrated by Figure 10. Furthermore, the use of a one-dimensional creep profile only shows the slopeward component of movement; this may well be a misleading representation of actual motion in a soil.

ACKNOWLEDGEMENTS

M.A.J.W. thanks the Australian National University, the former Division of Land Research and Regional Survey, CSIRO, Macquarie University, Monash University, and the Land Resources Section, Department of Northern Territory, for their help with field costs and transport. Our special thanks go to Mr and Mrs A. D. L. Hooper for encouragement and help during our visits to Darwin; to John and Gwen Horne, formerly of Khan Yunis Pastoral Property, for their hospitality; to R. Eves, R. Savage, F. Woerle, R. Wasson, J. Aldrick, A. Czacharowski and members of the Land Resources section in Darwin, who gave invaluable aid in the field. M.A.J.W. also thanks Dr Tom Dunne, Dr Bernard Hallet and their graduate students for fertile discussions during his visit to Seattle, and Dr Bruno Ambroise and an unidentified referee for detailed, thoughtful and constructive criticism.

REFERENCES

Auzet, A. -V. and Ambroise, B. 1996. 'Soil creep dynamics, soil moisture and temperature conditions on a forested slope in the granitic Vosges mountains, France', *Earth Surface Processes and Landforms,* **21**, 531–542.
Barr, D. J. and Swanston, D. N. 1970. 'Measurement of creep in a shallow, slide-prone till soil', *American Journal of Science,* **269**, 467–480.
Boussinesq, J. V. 1885. *Application des potentiels à l'étude de l'équilibre et du mouvement des solides élastiques*, Gauthier-Villars, Paris.
Carson, M. A. and Kirkby, M. J. 1972. *Hillslope Form and Process*, Cambridge University Press, Cambridge.
Culling, W. E. H. 1963. 'Soil creep and the development of hillside slopes', *Journal of Geology,* **68**, 336–344.
Culling, W. E. H. 1965. 'Theory of erosion on soil-covered slopes', *Journal of Geology,* **73**, 230–254.
Culling, W. E. H. 1983a. 'Steady state distributions in the measurement of soil creep', *Geographical Analysis,* **15**, 212–230.
Culling, W. E. H. 1983b. 'Rate process theory of geomorphic soil creep', in de Ploey, J. (Ed.), *Rainfall Simulation, Runoff and Erosion, Catena Supplement,* **4**, 191–214.
Culling, W. E. H. 1983c. Slow particulate flow in condensed media as an escape mechanism: mean translation distance', in de Ploey, J. (Ed.), *Rainfall Simulation, Runoff and Erosion, Catena Supplement,* **4**, 161–190.
Davison, C. 1889. 'On the creeping of the soil cap through the action of frost', *Geological Magazine,* **6**, 255–261.
Embleton, C. and King, C. A. M. 1968. *Glacial and Periglacial Geomorphology*, Edward Arnold, London, 608 pp.
Everett, K. R. 1963. *Slope movements in contrasting environments*, PhD thesis, Ohio State University (unpublished).
Eyles, R. J. and Ho, R. 1970. 'Soil creep on a humid tropical slope', *Journal of Tropical Geography,* **31**, 40–42.
Finlayson, B. 1981. 'Field measurements of soil creep', *Earth Surface Processes and Landforms,* **6**, 35–48.
Finlayson, B. L. 1985. 'Soil creep: a formidable fossil of misconception', in Richards, K. S., Arnett, R. R. and Ellis, S. (Eds), *Geomorphology and Soils*, George Allen and Unwin, London, 141–158.
Finlayson, B. L. and Osmaston, H. A. 1977. 'An instrument system for measuring soil movement', *British Geomorphological Research Group, Technical Bulletin,* **19**.
Haynes, C. D., Ridpath, M. G. and Williams, M. A. J. (Eds) 1991. *Monsoonal Australia: Landscape, ecology and man in the northern lowlands*, Balkema, Rotterdam, 243 pp.
Humphreys, G. S. 1985. *Bioturbation, rainwash and texture-contrast soils; an evaluation of transporting processes on soil genesis in the Sydney Basin*, PhD thesis, Macquarie University, Sydney, (unpublished).
Jahn, A. 1989. 'The soil creep on slopes in different altitudinal and ecological zones of Sudetes Mountains', *Geografiska Annaler,* **71**, 161–170.
Jennings, J. N. 1967. 'Two maps of rainfall intensity in Australia', *Australian Geographer,* **10**, 256–262.

Kallstenius, T. and Bergau, W. 1961. 'In situ determination of horizontal ground movements', *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering, Paris*, Vol. 1, 481–485.
Kirkby, M. J. 1967. 'Measurement of theory of soil creep', *Journal of Geology*, **75**, 359–378.
Lewis, L. A. 1976. 'Soil movement in the tropics – a general model', *Zeitschrift für Geomorphologie Supplementband,* **25**, 132–144.
Mitchell, P. B. 1988. 'The influence of vegetation, animals and micro-organisms on soil processes', in Viles, H. A. (Ed.), *Biogeomorphology*, 43–82.
Moeyersons, J. 1988. 'The complex nature of creep movements on steeply sloping ground in Southern Rwanda', *Earth Surface Processes and Landforms,* **13**, 511–524.
Moeyersons, J. 1989. 'A possible causal relationship between creep and sliding on Rwaza Hill, Southern Rwanda', *Earth Surface Processes and Landforms,* **14**, 597–614.
Owens, I. F. 1969. 'Causes and rates of soil creep in the Chilton Valley, Cass, New Zealand', *Arctic and Alpine Research,* **1**, 213–220.
Paton, T. R. 1978. *The Formation of Soil Material*, George Allen and Unwin, London, 143 pp.
Paton, T. R., Humphreys, G. S. and Mitchell, P. B. 1995. *Soils: A new global view*, University College London Press, London, 213 pp.
Rapp, A. 1962. 'Kärkevagge: some recordings of mass movements in the northern Scandinavian mountains', *Biul. peryglac.,* **11**, 287–309.
Reynolds, H. R. and Protopapadakis, P. 1959. *Practical Problems in Soil Mechanics*, Crosby, Lockwood and Son, London, 224 pp.
Rudberg, S. 1958. 'Some observations concerning mass movement in slopes in Sweden', *Geol. Foren. Stockholm Forh.,* **80**, 114–125.
Selby, M. J. 1968. 'Cones for measuring soil creep', *Journal of Hydrology (New Zealand),* **7**, 136–137.
Souchez, R. '1963. 'Evolution des versants et théorie de plasticité', *Revue Belge de Géographie,* **87**, 10–94.
Verster, E. and Van Rooyen, T. H. 1988. 'Measurement of soil movement on two hillslopes displaying terracettes in humid South Africa', in Dardis, G. F. and Moon, B. P. (Eds), *Geomorphological Studies in Southern Africa*, Balkema, Rotterdam, 311–320.
Ward, W. H. 1953. 'Soil movement and weather', *Proceedings of International Conference on Soil Mechanics and Foundation Engineering, 3d, Switzerland*, Vol. 1, 477–482.
Washburn, A. L. 1967. 'Instrumental observations of mass-wasting in the Mesters Vig district, Northeast Greenland', *Medd. om Grønland,* **166**(4), 1–318.
Washburn, A. L. 1973. *Periglacial Processes and Environments*, Edward Arnold, London, 320 pp.
Williams, M. A. J. 1968. 'Termites and soil development near Brock's Creek, Northern Territory', *Australian Journal of Science,* **31**, 153–154.
Williams, M. A. J. 1969a. *Rates of slopewash and soil creep in northern and southeastern Australia: A comparative study*, PhD thesis, Australian National University, Canberra, 318 pp (unpublished).
Williams, M. A. J. 1969b. 'Prediction of rainsplash erosion in the seasonally wet tropics', *Nature,* **222**, 763–765.
Williams, M. A. J. 1973. 'The efficacy of creep and slopewash in tropical and temperate Australia', *Australian Geographical Studies,* **11**, 62–78.
Williams, M. A. J. 1978a. 'Termites, soils and landscape equilibrium in the Northern Territory', in Davies, J. L. and Williams, M. A. J. (Eds), *Landform Evolution in Australasia*, Australian National University Press, 128–141.
Williams, M. A. J. 1978b. 'Late Holocene hillslope mantles and stream aggradation in the Southern Tablelands, N.S.W.', *Search,* **9**, 96–97.
Williams, M. A. J. 1991. 'Evolution of the landscape', in Haynes, C. D., Ridpath, M. G. and Williams, M. A. J. (Eds), *Monsoonal Australia: Landscape, ecology and man in the northern lowlands, Balkema, Rotterdam, 5–17.*
Williams, P. J. 1957. 'The direct recording of solifluction movements', *American Journal of Science,* **255**, 705–715.
Young, A. 1960. 'Soil movement by denudational processes on slopes', *Nature,* **188**, 120–122.
Young, A. 1972. *Slopes*, Oliver and Boyd, 288 pp.
Young, A. 1978. 'A twelve-year record of soil movement on a slope', *Zeitschrift für Geomorphologie Supplementband,* **29**, 104–110.